

## FINDING RADIO PULSARS IN AND BEYOND THE GALACTIC CENTER

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## ABSTRACT

Radio-wave scattering is enhanced dramatically for galactic center sources in a region with radius  $\gtrsim 15$  arc min. Using scattering from Sgr A\* and other sources, we show that pulse broadening for pulsars in the Galactic center is *at least*  $6.3 \nu^{-4}$  seconds ( $\nu$  = radio frequency in GHz) and is most likely 50–200 times larger because the relevant scattering screen appears to be within the Galactic center region itself. Pulsars beyond—but viewed through—the Galactic center suffer even greater pulse broadening and are angularly broadened by up to  $\sim 2$  arc min. Periodicity searches at radio frequencies are likely to find only long period pulsars and, then, only if optimized by using frequencies  $\gtrsim 7$  GHz and by testing for small numbers of harmonics in the power spectrum. The optimal frequency is  $\nu \sim 7.3 \text{ GHz} (\Delta_{0.1} P \sqrt{\alpha})^{-1/4}$  where  $\Delta_{0.1}$  is the distance of the scattering region from Sgr A\* in units of 0.1 kpc,  $P$  is the period (seconds), and  $\alpha$  is the spectral index. A search for compact sources using aperture synthesis may be far more successful than searches for periodicities because the angular broadening is not so large as to desensitize the survey. We estimate that the number of *detectable* pulsars in the Galactic center may range from  $\leq 1$  to 100, with the larger values resulting from recent, vigorous starbursts. Such pulsars provide unique opportunities for probing the ionized gas, gravitational potential, and stellar population near Sgr A\*.

*Subject headings:* scattering — pulsars: general — Galaxy: center

## 1. INTRODUCTION

Only 15 radio pulsars of the current catalog of approximately 700 are within  $5^\circ$  of Sgr A\* and none are within  $1^\circ$  (Taylor, Manchester, & Lyne 1993). Discovering pulsars in or near the Galactic center (GC) would provide exciting opportunities for probing magnetized material, the gravitational potential, and star formation in the GC (e.g., Hartmann 1995; Sofue 1994). Counterparts to X- and  $\gamma$ -ray GC sources may also involve radio pulsars or their progenitors. Moreover, dynamical constraints on the mass in the GC combined with infrared observations suggest that neutron stars may abound there.

It may be impossible to find radio pulsars in the GC as sources of periodic radio emission, however. The difficulty arises because radio-wave scattering, which is particularly severe from sources in the GC (e.g., Sgr A\*, Backer et al. 1993; Lo et al. 1993; Backer 1988; and several OH/IR stars, Frail et al. 1994; van Langevelde et al. 1992), broadens pulsar pulses by extraordinary amounts. The actual level of angular broadening toward the GC at 1 GHz is  $\sim 10$  times greater than that predicted by a recent model for the distribution of free electrons in the Galaxy (Taylor & Cordes 1993; hereafter TC), even though this model includes a general enhancement of scattering toward the inner Galaxy. For pulsars in the GC, the resultant pulse broadening is at least 100 times larger than predicted by the TC model. The TC model purposely excluded an explicit treatment of the electron density in the GC, primarily because it would have been, at best, poorly quantified. More recent data on angular broadening of GC sources, however, now allows us to estimate the amount by which pulse broadening should be augmented. Our results complement recent work (Johnston 1994) that suggests a paucity of pulsars inside of the molecular ring at Galactocentric radius  $\sim 4$  kpc. Johnston (1994) considered a large-scale region toward the inner Galaxy and did not discuss the immediate vicinity of the GC.

Pulse broadening is so large in the GC that, at conventional frequencies used for pulsar searches, 0.4–1.4 GHz, the pulsed flux is orders of magnitude too small to be detected, as we show below. The strong frequency dependence of pulse broadening ( $\propto \nu^{-4}$ ) suggests that frequencies at much higher frequencies, 5–20 GHz, will mitigate the effects of scattering. But pulsar spectra generally decline at higher frequencies, sometimes precipitously, making this option un-

likely to find many pulsars. However, some pulsars have been detected at frequencies as high as 30 GHz (Xilouris et al. 1995; Seiradakis et al. 1995; Izvekova et al. 1994; Kramer et al. 1994; Malofeev et al. 1994). Though these are relatively nearby objects, their detections suggest that some pulsars may show sufficient spectral flattening that they would be detectable if as far as the GC.

In this paper we discuss pulse broadening from sources in and beyond the GC. We show how to optimize a periodicity search in terms of radio frequency and number of harmonics. We also discuss searches for pulsars as steady sources rather than periodic ones. Namely, we show that aperture synthesis surveys using the Very Large Array (VLA), for example, should be successful in finding objects with pulsar-like spectra and polarization.

In §2 we detail the assumed geometry and angular broadening. In §3 we derive the resulting pulse broadening timescales. §4 discusses the pessimistic implications of pulse broadening for pulsar surveys involving periodicity searches. In §5 we argue that aperture synthesis surveys may be more successful than periodicity searches in identifying radio pulsars in the GC. In §6 we estimate the likely number of pulsars in the GC. In §7 we present our conclusions and recommendations.

## 2. ANGULAR BROADENING AND THE SCATTERING GEOMETRY

The angular diameter of Sgr A\* is  $1.3''$  at 1 GHz and scales as  $\nu^{-2}$ , in accord with interstellar scattering (Lo et al. 1993). OH/IR stars in the vicinity of the GC also show very heavy scattering, at least for those stars within  $\sim 15'$  of Sgr A\* (Frail et al. 1994; van Langevelde et al. 1992). We use the measured angular broadening to predict the pulse broadening expected from pulsars in the GC, but with the following caveat: we must assume the location along the line of sight of the scattering “screen” that enhances the scattering. As van Langevelde et al. (1992) discuss, the location of the screen is by no means determined and has implications for the depth of free-free absorption to the GC and the outer scale of the electron-density variations. For now, we treat the location of the screen as a parameter of the overall geometry. We constrain its location using recent scattering measurements for the GC region (Lazio, Cordes & Frail 1996).

We model the scattering as arising from a discrete

screen, as in the top of Fig. 1. Let  $\theta_s$  be the scattering angle produced by the screen and  $\theta_o$  the observed scattering angle. In the following we assume the small-angle approximation:  $\theta_s, \theta_o \ll 1$ . For a source at infinite distance,  $\theta_o \equiv \theta_s$  because the waves incident on the screen are plane waves. Sources at finite distance are scattered less due to wave sphericity. If the source is at distance  $D$  and the screen is in front of the source by distance  $\Delta$ , the observed scattering angle is  $\theta_o = (\Delta/D)\theta_s$ . If the scattering screen is very close to the GC, then  $\Delta \ll D$  and the observed scattering diameter of an extragalactic source is

$$\theta_{\text{xgal}} = \left( \frac{D_{\text{GC}}}{\Delta_{\text{GC}}} \right) \theta_{\text{GC}} \gg \theta_{\text{GC}}, \quad (1)$$

where  $\theta_{\text{GC}}$  is the observed scattering diameter of Sgr A\*. If the scattering screen is, in fact, associated with the GC (e.g.,  $D_{\text{GC}} \lesssim 100$  pc), then extragalactic sources viewed through the screen necessarily have angular diameters that exceed 1 *arc min* at 1 GHz.

The screen geometry we have utilized is highly idealized. Other, more physical, geometries are also presented in Fig. 1. The scattering screen may *surround* the GC with spherical or cylindrical geometry. Alternately, the scattering region may be distributed throughout the GC region rather than being confined to a thin screen. Yusef-Zadeh et al. (1994), for example, interpret anisotropic scattering from Sgr A\* in terms of H II regions distributed uniformly within 100 pc of Sgr A\*. The scattering from Sgr A\* may then be *effectively* screen-like because it will be dominated by H II regions farthest from Sgr A\* (through geometric effects). However, background sources will be scattered by all H II regions. In these cases, the angular diameters of background sources are at least double what we have derived if the scattering is from a thin screen that surrounds the GC, but it will be even greater for scattering regions that fill the GC.

Van Langevelde et al. (1992) derived a lower bound on the GC-screen distance based on the fact that the free-free optical depth must be  $\lesssim 1$  at 1.6 GHz:

$$\Delta_{\text{GC}} \gtrsim 0.1 D_{\text{GC}} \left( \frac{\ell_1}{100 \text{ km}} \right)^{1/6} \left( \frac{\ell_0}{1 \text{ pc}} \right)^{1/3} \left[ \frac{g(\nu, T)}{T_4^{1.5}} \right]^{1/2} \quad (2)$$

In this equation,  $\ell_0$ ,  $\ell_1$  are the outer and inner scales, respectively, of the electron-density fluctuations;  $g(\nu, T)$  is the Gaunt factor, and  $T_4$  is the temperature in units of  $10^4$  K. The various parameters

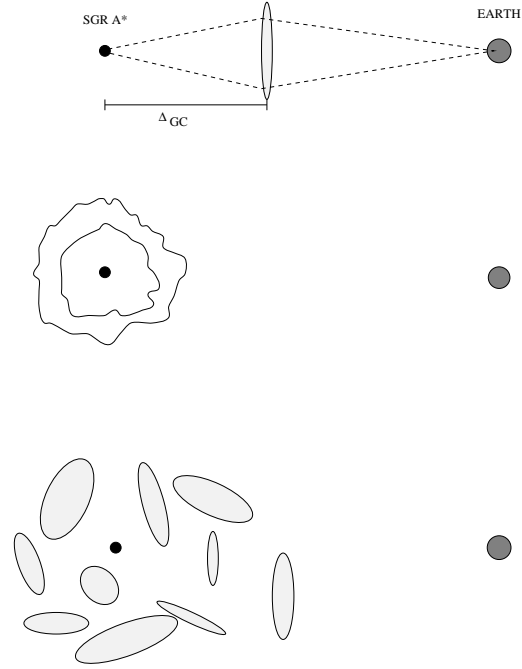


Fig. 1.— Geometries for the Galactic Center scattering region. (Top) A single, thin screen located a distance  $\Delta_{\text{GC}}$  from the Galactic center. This geometry is used in most of the discussion in this paper. (Middle) A spherical (or cylindrical) shell surrounding the GC. (Bottom) A scattering region composed of “screenlets” distributed around the GC with total size  $\sim \Delta_{\text{GC}}$ .

can be adjusted to reduce the overall coefficient from 0.1 to 0.004 (e.g., through an inner scale of 0.01 pc and a temperature of  $10^5$  K). However, even  $10^5$  K may be too hot for electron density variations to be sustained (e.g., Spangler 1991). A scattering screen thinner than 0.01 pc is also improbable because stellar-wind shocks tend to be at least this thickness (Kahn & Breitschwerdt 1990). The outer scale, which is probably comparable to the screen thickness, cannot be reduced much below 0.01 pc. Other evidence also indicates that the inner scale is not less than 100 km. This includes the observed scaling of scattering diameters as  $\nu^{-2}$  for Sgr A\* and other heavily scattered sources such as Cyg X-3 (Molnar et al. 1995; Wilkinson, Narayan, & Spencer 1994) and

NGC6334B (Moran et al. 1990). We therefore take as a hard lower bound,  $\Delta_{\text{GC}} \geq 33$  pc. This suggests that a strong upper bound on the sizes of extragalactic sources is  $\theta_{\text{xgal}} \lesssim 11'$  for a screen-like geometry that wraps around Sgr A\*.

It is possible to determine the screen distance from the Galactic center by either measuring the diameters of extragalactic sources or, in the case where severe scattering diminishes our ability to detect sources, use the deficiency of sources to constrain the screen location. Attempts to observe extragalactic sources near Sgr A\* in fact show a deficiency of sources within  $0.5^\circ$  of Sgr A\* (Lazio et al. 1996). A likelihood analysis shows that this deficiency is consistent with extragalactic source sizes larger than  $0.5'$  and  $\Delta_{\text{GC}} \lesssim 200$  pc (Lazio et al. 1996).

### 3. PULSE BROADENING

Pulse broadening is a diffraction phenomenon but may be treated with stochastic ray tracing through extended media (Williamson 1972, 1975). It has been observed for many pulsars and used to study the distribution of ionized microturbulence in the Galaxy (Cordes et al. 1991).

The pulse broadening due to the screen responsible for the scattering of Sgr A\* has an  $e^{-1}$  time scale

$$\tau_{\text{GC}}(D_{\text{GC}}) \sim f \left( \frac{\Delta_{\text{GC}}}{D_{\text{GC}}} \right) \left( \frac{D_{\text{GC}} \theta_{\text{GC}}^2}{8c \ln 2} \right), \quad (3)$$

where the screen's location along the line of sight is represented by the geometric factor<sup>1</sup>

$$f(x) \equiv x^{-1}(1-x). \quad (4)$$

The pulse broadening time for fiducial values of the distance (8.5 kpc) and scattering diameter ( $1.3''$ ) at a frequency of 1 GHz is

$$\tau_{\text{GC}}(D_{\text{GC}}) \sim 6.3 \left( \frac{D_{\text{GC}}}{8.5 \text{ kpc}} \right) \left( \frac{\theta_{\text{GC}, 1 \text{ GHz}}}{1.3''} \right)^2 \nu_{\text{GHz}}^{-4} f \left( \frac{\Delta_{\text{GC}}}{D_{\text{GC}}} \right) 5$$

In Eq. 5 we have adopted a frequency scaling  $\propto \nu^{-4}$  rather than the often encountered  $\nu^{-4.4}$  scaling because, in the extremely strong scattering limit, the scattering is dominated by the smallest irregularities

in the free electron density that are physically present (cf. Cordes & Lazio 1991). This is consistent with the observed  $\nu^{-2}$  scaling of the angular diameter of Sgr A\*. The geometric factor is  $f \rightarrow 1$  if the screen is midway along the line of sight. But for screens very near the GC,  $f \rightarrow x^{-1} \gg 1$ . Therefore, pulsars at the same location as the GC will show *at least* 6.3 s of pulse broadening at 1 GHz<sup>2</sup>. The pulse broadening may be significantly larger, perhaps as much as 200 times larger, because the scattering screen may be only 33–100 pc from the GC. The minimal scattering time of 6.3 s may be compared, at 1 GHz, to the pulse broadening of the most heavily scattered pulsar, PSR B1849–00 (Frail & Clifton 1989; Clifton et al. 1987), which is about 0.3 s.

Pulsars beyond the GC (but still behind the scattering screen) will show even larger scattering. For a pulsar distance  $D \geq D_{\text{GC}} - \Delta_{\text{GC}}$ , the pulsar-screen distance is  $\Delta \equiv D - D_{\text{GC}} + \Delta_{\text{GC}}$  and the pulse broadening from the screen is

$$\tau_{\text{GC}}(D) \sim \tau_{\text{GC}}(D_{\text{GC}}) \left( \frac{D_{\text{GC}}}{D} \right) \left( \frac{\Delta}{\Delta_{\text{GC}}} \right). \quad (6)$$

As a function of distance from the Sun, pulse broadening increases slowly and according to the TC model, which possesses components that grow stronger in the inner Galaxy. Then, just beyond the location of the GC scattering screen, pulse broadening increases dramatically and continues to increase. To combine the TC model and the GC screen component, we write the net pulse broadening as

$$\tau = \begin{cases} \tau_{\text{TC}}, & D < D_{\text{GC}} - \Delta_{\text{GC}}; \\ (\tau_{\text{TC}}^2 + \tau_{\text{GC}}^2)^{1/2}, & D \geq D_{\text{GC}} - \Delta_{\text{GC}}. \end{cases} \quad (7)$$

Combining the TC and GC-screen scattering times is *ad hoc* in form but is sufficiently accurate for our purposes here because the GC component is much larger than the TC contribution.

Figure 2 shows the pulse broadening at two frequencies (1.4 and 10 GHz) for a range of GC-screen distances,  $\Delta_{\text{GC}} = 0.05, 0.1, 0.2, 1.0,$  and  $4.25$  kpc. For pulsars beyond the GC, the pulse broadening asymptotes to  $\tau_{\text{GC}}(D_{\text{GC}})(D_{\text{GC}}/\Delta_{\text{GC}}) \sim 10^5$  s at 1.4 GHz and 18 s at 10 GHz.

<sup>1</sup>Pulse broadening is often expressed in terms of the *screen* scattering angle  $\theta_s$  rather than the observed angle  $\theta_o$ . Using  $\theta_s$ , the equivalent geometric factor is  $x(1-x)$ , which maximizes at  $x = 1/2$ .

<sup>2</sup>An early analysis (Davies, Walsh & Booth 1976) estimated 10 s of pulse broadening at 1 GHz while implicitly assuming the scattering region to be midway between us and the GC.

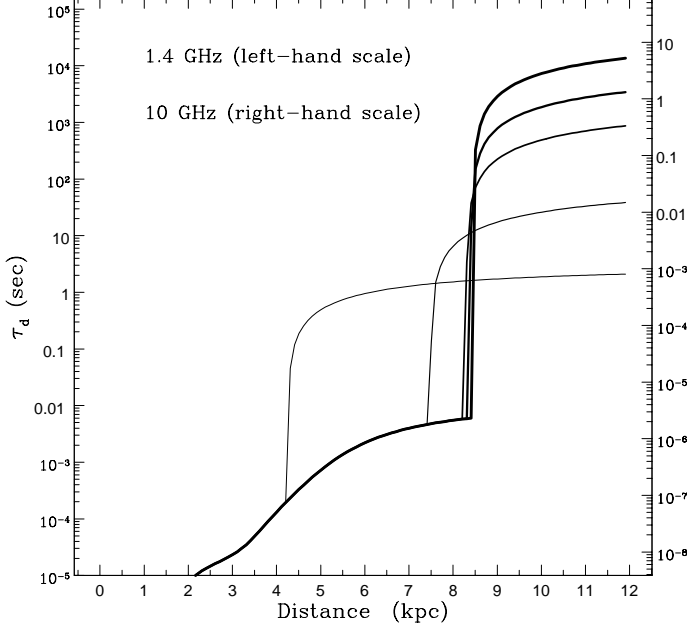


Fig. 2.— Pulse broadening is plotted against distance for 5 separate values of the GC-screen distance,  $\Delta_{\text{GC}}$ : 0.05 kpc (thickest line), 0.1, 0.2, 1.0, and 4.25 kpc (thinnest line). The left-hand scale applies to 1.4 GHz, the right-hand scale to 10 GHz. Broadening at other frequencies may be estimated using the assumed  $\nu^{-4}$  scaling.

#### 4. DETECTION OF SCATTERED PULSARS IN PERIODICITY SEARCHES

Pulse broadening decreases the number of harmonics that exceed a predetermined threshold in the power spectrum of the intensity, thus reducing the sensitivity of a pulsar search. Consider a train of pulses with period  $P$ , average pulse area  $A_0$ , duty cycle  $\epsilon$ , and pulse width (FWHM)  $W \equiv \epsilon P$ . The discrete Fourier transform of the pulse train is a series of spikes at frequencies  $\ell/P$ ,  $\ell = 0, 1, \dots$  each having an amplitude,

$$\mathcal{A}_{\text{DFT}}(\ell) = A_0 \tilde{g}(\epsilon \ell), \quad (8)$$

where pulses have a generic shape  $g(\phi)$  in pulse phase  $\phi$ , whose continuous Fourier transform is  $\tilde{g}$ .

We define the *intrinsic* pulsed fraction of the pulsar flux as the ratio of the fundamental frequency and zero frequency (“DC”) amplitudes:

$$\eta_P \equiv \left| \frac{\mathcal{A}_{\text{DFT}}(1)}{\mathcal{A}_{\text{DFT}}(0)} \right| = \left| \frac{\tilde{g}(\epsilon)}{\tilde{g}(0)} \right| = \exp \left[ - \left( \frac{\pi \epsilon}{2\sqrt{\ln 2}} \right)^2 \right]. \quad (9)$$

where the third equality is for gaussian-shaped pulses [i.e.,  $g(\phi) = \exp(-4 \ln 2 \phi^2)$ ]. For most pulsars,  $\epsilon \lesssim 0.1$  implying  $\eta_P \sim 1$ .

Broadening increases the pulse width to  $W_{\text{eff}} \sim (W^2 + \tau^2)^{1/2}$  and, hence, the duty cycle to  $\epsilon_{\text{eff}} \equiv W_{\text{eff}}/P$ . The pulsed fraction becomes

$$\eta_P^{(s)} = \eta_P \left| \frac{\tilde{g}(\epsilon_{\text{eff}})}{\tilde{g}(\epsilon)} \right| \approx \exp \left[ - \left( \frac{\pi \tau}{2\sqrt{\ln 2} P} \right)^2 \right]. \quad (10)$$

Figure 3 shows the pulsed fraction plotted against frequency for five different pulse periods. We have assumed that the GC screen is near Sgr A\* ( $\Delta_{\text{GC}} = 50$  pc).

Most pulsars have radio spectra that are power-laws in form, some objects displaying one or more break points separating power-laws of different slope (Lorimer et al. 1995). Letting the spectrum be  $S_\nu \propto \nu^{-\alpha}$ , we maximize the *pulsed* flux density  $\eta_P^{(s)} S_\nu$  against frequency to solve for the corresponding optimal pulse broadening,  $\tau_{\text{max}} = (\alpha \ln 2/2)^{1/2} P/\pi$ . The frequency at which the pulsed flux density is maximized can be found from Eq. 5 as

$$\begin{aligned} \nu_{\text{max}} &= 2.41 \text{ GHz} \left( \frac{f}{\sqrt{\alpha} P} \right)^{1/4} \\ &\sim 7.3 \text{ GHz} (\sqrt{\alpha} \Delta_{0.1} P)^{-1/4}, \end{aligned} \quad (11)$$

where  $\Delta_{0.1} \equiv \Delta_{\text{GC}}/0.1 \text{ kpc}$ . Note that the optimal frequency is a function of pulse period. At the optimal frequency, the pulsed fraction is  $\eta_P^{(s)} = e^{-\alpha/8}$  and the pulse broadening yields an effective duty cycle

$$\epsilon_{\text{eff}} = (\epsilon^2 + \alpha \ln 2/2 \pi^2)^{1/2} \approx 0.19 \sqrt{\alpha}. \quad (12)$$

The approximate equality is for the case where  $\epsilon \ll 0.2$  and suggests that, for such pulsars, the search algorithm should search for no more than  $\epsilon_{\text{eff}}^{-1} \sim 5$  harmonics in the Fourier transform. Figure 4 shows  $\eta_P^{(s)} S_\nu$  plotted against frequency for several pulse periods,  $P$ , and spectral indices,  $\alpha$ .

There is a barrier of indetectability at low frequencies. It is obvious that only very luminous,

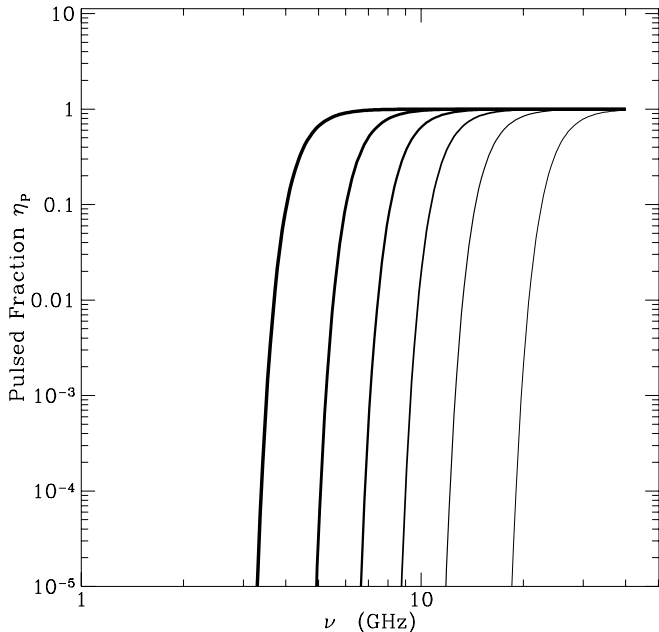


Fig. 3.— Plot of the pulsed fraction  $\eta_p^{(s)}$  against frequency  $\nu$  for different pulse periods,  $P = 5$  s (thickest line), 1 s, 0.3 s, 0.1 s, 30 ms, & 5 ms (thinnest line). The scattering screen is assumed to be close to the GC,  $\Delta_{GC} = 50$  pc. If the screen is more distant from the GC than 50 pc, the plotted curves move toward the left.

long period pulsars with shallow spectra are candidates for detection. The most luminous pulsars are those that show “core” emission (Rankin 1990). A good example is B1933+16 with  $P = 0.36$  s, distance  $D = 7.9$  kpc, and period-averaged flux densities  $S_{400} = 242$  mJy and  $S_{1400} = 42$  mJy at 400 and 1400 MHz, respectively (Taylor et al. 1993). If placed at the GC, the pulsed fraction of this pulsar  $\geq e^{-1}$  for  $\nu \geq 2.4f^{1/4}$  GHz. With  $\alpha = 1.4$  and  $f = 170$  (i.e.,  $\Delta_{GC} = 50$  pc), we find that  $\nu_{\max} \approx 10.8$  GHz. At this frequency, the pulsed flux of B1933+16 is 1.8 mJy if placed at the GC. Pulsar surveys can reach this flux density through use of large bandwidths (e.g., 1 GHz). For pulsars in general, we find that the optimal range of search frequencies is  $5 \text{ GHz} \lesssim \nu_{\max} \lesssim 18 \text{ GHz}$  for  $0.5 \lesssim \alpha \lesssim 2$  and  $0.1 \lesssim P \lesssim 5$  s.

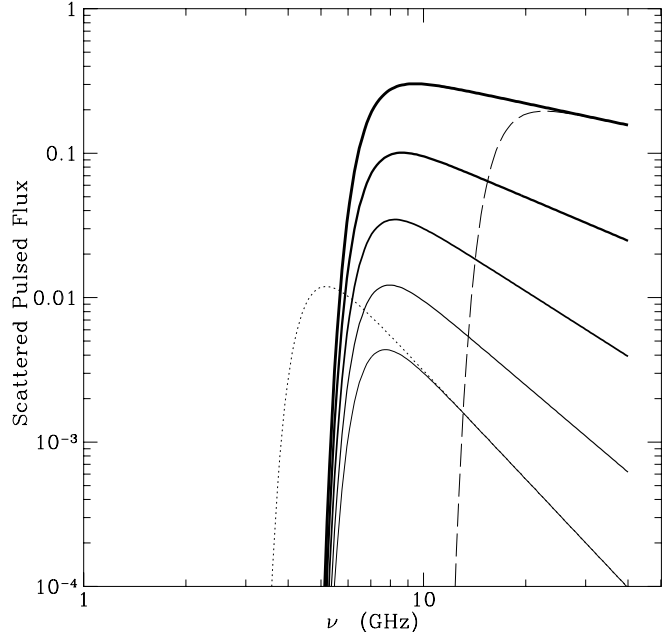


Fig. 4.— The pulsed flux, taking scattering into account, as a function of frequency. Pulsar spectra of the form  $\nu^{-\alpha}$  have been normalized so that the flux at 1 GHz is the same for all  $\alpha$ . The intrinsic pulse duty cycle is  $\epsilon = 0.05$ . *Solid Lines*:  $P = 1$  s for  $\alpha = 0.5$  (heaviest line), 1, 1.5, 2, 2.5 (thinnest line). *Dotted Line*:  $P = 5$  s and  $\alpha = 2.5$ . *Dashed Line*:  $P = 30$  ms and  $\alpha = 0.5$ .

The frequency of maximum, pulsed flux, as we have defined it, does not correspond to the frequency where S/N is maximized in a Fourier transform search. Maximizing S/N depends on the number of harmonics detectable in the DFT, and on the variation of system temperature with frequency. At the optimal frequency, where approximately  $\epsilon_{\text{eff}}^{-1} \sim 5$  DFT spikes should be detectable, the S/N can be increased by a factor  $\sim \sqrt{5}$ .

We conclude this section with an example search program for finding GC pulsars in periodicity searches (see Table 1). We consider searches at 5, 8, 10.8 and 15 GHz on a telescope with sensitivity equal to that for the National Radio Astronomy Observatory’s Green Bank Telescope, now under construction. The

minimum flux density for a single harmonic in the DFT is

$$S_{\min} = \frac{\eta_T T_{\text{sys}}}{G \sqrt{\Delta \nu T}} \sim 130 \mu\text{Jy}, \quad (13)$$

where  $T_{\text{sys}}$  is the system temperature, assumed to be 50 K,  $G \sim 2$  K/Jy is the telescope gain, the receiver bandwidth is  $\Delta \nu = 1$  GHz, and the total observing time is  $T = 1$  hr. The signal-to-noise threshold for detection of a signal is assumed to be  $\eta_T = 10$ . The 1-GHz bandwidth is substantially larger than that used in most surveys but is quite feasible at high frequencies. Moreover, only coarse channelization is required to combat dispersion smearing. For dispersion measures as large as  $2000 \text{ pc cm}^{-3}$ , only about 16 channels are needed. The results in Table 1 illustrate an analysis of the fundamental only; as discussed above, analysis of higher harmonics could improve the quoted sensitivities by a factor of  $\sim 2$ .

Two different measures of a search's ability to detect pulsars are illustrated in Table 1. The first is its ability to detect B1933+16, if it were placed in the GC. Entries in the Table suggest that large S/N can be achieved at frequencies greater than 8 GHz. Detection at 5 GHz is hopeless. We also assess the fraction of the total GC pulsar population that a search could detect, which we determine from the luminosity function for radio pulsars. In the solar neighborhood, for observation frequencies near 400 MHz, the pulsar luminosity function has the form  $dN/d\log L \propto L^{-\beta}$  with  $\beta \approx 1$  (Lyne, Manchester, & Taylor 1985; Manchester & Taylor 1977). The fraction of sources with luminosity greater than  $L$  is  $f_L(> L) \approx (1 - L/L_1)L_0/L$ , where  $L_0, L_1$  are the minimum and maximum *intrinsic* luminosities of a pulsar. In the most recent catalog of pulsars (Taylor et al. 1993), only one pulsar has a luminosity less than  $1 \text{ mJy kpc}^2$ , so we take  $L_0 = 1 \text{ mJy kpc}^2$ . We use a spectral index of 1.4 to scale in frequency. For  $S_{\min}$  given by Eq. 13, the implied minimum luminosity at the particular observation frequency is  $\sim 11 \text{ mJy kpc}^2$ . Scaling *from* the frequencies in the Table then yields the equivalent  $L$  at 400 MHz and the fraction of objects that exceed this minimum. We also tabulate the period,  $\tilde{P}$ , at which the tabulated frequency is, in fact, the optimal frequency, as given by Eq. 11. As can be seen, this period exceeds that of any known radio pulsar at 5 GHz, but decreases progressively to  $\sim 0.1$  s at 15 GHz. The fraction of objects that exceed the minimum luminosity also decreases in going from 5 to 15 GHz. A key disadvantage to us-

ing higher frequencies is that, all other things being equal, the telescope time needed to search a region of fixed angular size will scale as the solid angle of the telescope beam,  $\propto \nu^{-2}$ . This amounts to nearly an order of magnitude increase in time needed in going from 5 to 15 GHz.

The results in Table 1 are only illustrative. Pulsars show a wide range of spectral indices and there are possible correlations between period and luminosity that we have ignored. Also, we have been assuming a constant pulse-broadening value for pulsars in the GC. In actuality, the spatial distribution of pulsars in the GC will create a range of pulse broadening. The extreme values of pulse broadening we have estimated above will be obtained if the angular distribution of pulsars is concentrated toward Sgr A\*, yet are still quite far from the scattering screen. However, pulsars spread throughout the region will show a wide range of broadening. Objects close to the screen will show small scattering, asymptotic to the TC value as  $\Delta_{\text{psr}} \rightarrow 0$ . Periodicity searches at different (high) frequencies will therefore sample the population at different  $\Delta_{\text{psr}}$ .

## 5. SEARCHES FOR PULSARS IN IMAGING SURVEYS FOR POINT SOURCES

Scattering preserves the total flux density while attenuating the pulsed flux. Pulsars may therefore be searched for as objects with pulsar-like spectra and polarization in aperture synthesis surveys of the GC. Angular broadening dilutes the surface brightness, but we show here that this dilution denigrates a synthesis survey far less than pulse broadening does a periodicity search. Indeed Sgr A\*, the OH/IR stars (§1), and the GC transient (Zhao et al. 1992) demonstrate that heavily scattered, yet sufficiently luminous, sources in the GC can be detected with aperture synthesis instruments.

Table 2 illustrates detection of pulsars in an imaging survey with the VLA. We assume observations are conducted with a total integration time of 1 hr and total bandwidth  $\Delta \nu = 50$  MHz at 1.4 and 5 GHz and  $\Delta \nu = 3$  MHz at 0.33 GHz. As before, we consider the detection of both B1933+16 and a fraction of the total pulsar population (§4). Recent observations at 0.33 GHz (e.g., Frail et al. 1995) have demonstrated the capability of making low-frequency observations with the VLA which approach the thermal noise limit in the A-configuration. Within Sgr A West, i.e.,

TABLE 1  
PULSAR DETECTION IN PERIODICITY SEARCHES

$\nu$ (GHz) (1)	$\tau_{\text{GC}}$ (s) (2)	$S_{\text{sys}}$ (Jy) (3)	$S_{\text{min}}$ ( $\mu\text{Jy}$ ) (4)	B1933+16		$\tilde{P}$ (s) (7)	$f_L$ (8)
				$\eta_P^{(s)} S_\nu$ (mJy) (5)	( $S/N$ ) (6)		
5	1.7	25	130	0	$\ll 1$	7.8	$10^{-2.6}$
8	0.26	25	130	0.5	38	1.2	$10^{-2.9}$
10.8	0.08	25	130	1.8	138	0.4	$10^{-3.1}$
15	0.021	25	130	1.6	123	0.1	$10^{-3.3}$

NOTE.—(1) Observation frequency; (2) Pulse-broadening time for  $\Delta_{\text{GC}} = 50$  pc; (3)  $S_{\text{sys}} = T_{\text{sys}}/G$ , where  $G$  is the telescope sensitivity in  $\text{K Jy}^{-1}$ ; (4) Minimum detectable flux of fundamental in FFT; (5) Pulsed flux density of PSR B1933+16; (6) Signal-to-noise ratio for a search of PSR B1933+16, if it were at the Galactic center; (7) Period for which the frequency is the optimum search frequency. (8) Fraction of total pulsar population likely to be detectable, assuming nominal spectral index of  $-1.4$

within 5 arc min of Sgr A\*, strong thermal absorption is seen at 0.33 GHz. This absorbing gas strongly attenuates Sgr A\* below 1 GHz (Anantharamaiah et al. 1991; Pedlar et al. 1989) and may contribute to the extreme scattering of Sgr A\* at higher frequencies. However, heavily scattered OH masers are seen up to 25 arc min from Sgr A\* (Frail et al. 1994). Over this larger region, the free-free optical depth is only  $\sim 1$ . Therefore, absorption may attenuate source fluxes but should not render the entire scattering region opaque.

For the Table, we have assumed that pulsar scattering diameters are the same as that of Sgr A\*. From considerations in §2, the scattering diameter of a pulsar at distance  $D > D_{\text{GC}} - \Delta_{\text{GC}}$  is

$$\theta_{\text{psr}}(D) = \left(1 + \frac{D - D_{\text{GC}}}{\Delta_{\text{GC}}}\right) \left(\frac{D_{\text{GC}}}{D}\right) \theta_{\text{GC}}. \quad (14)$$

Pulsars closer to the screen than Sgr A\* will show less angular broadening than Sgr A\* while a pulsar only  $\Delta_{\text{GC}}$  further than Sgr A\* will be twice the diameter. An object 0.5 kpc beyond Sgr A\* will be 10 times the diameter (for  $\Delta_{\text{GC}} = 50$  pc), or  $13'' \nu_{\text{GHz}}^{-2}$ . The angular diameters of pulsars in the vicinity of Sgr A\* are therefore well matched to the synthesized beams of the VLA in its four configurations, though only the larger configurations filter out the intense extended

emission sufficiently. Note that the pulsar B1933+16 is easily detectable if placed in the GC at 1.4 as well as 5 GHz. Moreover, about 1.2% of all pulsars will be detectable at 1.4 GHz (for an assumed spectral index of 1.4), about 10 times larger than the fraction found in a periodicity search.

## 6. GALACTIC CENTER PULSAR POPULATIONS

The preceding sections have assumed the existence of pulsars in the GC. In this section we assess how many pulsars are likely to exist in the GC and use the results of §§4 and 5 to indicate how many of these are in fact detectable. The possibility of a large number of stellar remnants at the GC has been discussed by a number of other authors, though their focus has been on the central few parsecs (e.g., Saha, Bicknell, & McGregor 1996) and on either black holes (Morris 1993) or white dwarfs (Haller et al. 1996). Our focus will be on neutron stars exclusively and, based on the size of the scattering region, will be on a larger size scale than considered previously. We estimate the number of GC pulsars by considering both the integrated star formation history of the GC and the effects of a recent star burst. Finally, we also discuss the implications of the detection of GC pulsars on our understanding of



TABLE 2  
PULSAR DETECTION IN AN IMAGING SURVEY

$\nu$ (GHz) (1)	$\theta_{\text{GC}}$ (") (2)	$I_{\text{min}}$ (mJy/beam) (3)	B1933+16		$f_L$ (6)
			$I$ (mJy/beam) (4)	( $S/N$ ) (5)	
0.3	11	2.1 <sup>a</sup>	40	19	0.007
1.4	0.62	0.17	33	194	0.012
5	0.05	0.13	6.7	52	0.002

NOTE.—(1) Observation frequency; (2) Scattering angle for Galactic center source (i.e., Sgr A\*); (3) Minimum detectable brightness; (4) Brightness of PSR B1933+16, if it were at the Galactic center; (5) Signal-to-noise ratio for a search of PSR B1933+16, if it were at the Galactic center; (6) Fraction of total pulsar population likely to be detectable, assuming nominal spectral index of  $-1.4$

<sup>a</sup>Assumes bandwidth at 0.33 GHz of  $\Delta\nu = 3$  MHz.

the dynamics and star formation history of the GC.

We first consider the number of pulsars likely to have been formed if the star formation in the GC has been occurring at a constant rate over the Galaxy's history. In actuality, factors such as episodic star bursts, an initial mass function (IMF) different from that in the disk, and the shape of the central potential and its effects on gas dynamics may all have contributed to a variable star formation rate. The assumption of a constant star formation rate is nonetheless useful for illustration and comparison with the starburst model.

### 6.1. Steady Star Formation

We extrapolate from the current mass of the GC, for an assumed IMF, in order to estimate the number of pulsars likely to have formed within the GC. Various methods, summarized by Genzel, Hollenbach, & Townes (1994), constrain the mass enclosed within the central 100 pc to be in the range  $\sim 4 \times 10^8$ – $10^9 M_{\odot}$ . An estimate of the enclosed mass derived from the stellar luminosity distribution, and assuming a constant mass-to-light ratio, is approximately  $7 \times 10^8 M_{\odot}$ , which we adopt as a nominal value for the mass interior to 100 pc. Most of this mass is in the form of stars (Genzel et al. 1994). Because we do not know the form of the IMF in the GC, we consid-

ered different IMFs, one appropriate for the Galactic disk (Miller & Scalo 1979) and one that accounts for a stronger weighting of the IMF toward high-mass stars during starbursts (Rieke et al. 1980). For these IMFs, and different assumed ranges of masses for main-sequence stars that result in neutron stars, we find that  $4$ – $12 \times 10^7$  neutron stars have formed in the GC.

Implicit in this extrapolation is the assumption that star formation and evolution in the GC is similar to that in the disk. Morris (1993) has discussed the conditions in the central 1–10 pc and how they could both inhibit massive star formation and alter the evolution of those stars which do form. Meynet et al. (1994) have shown that massive, high-metallicity stars may lose a substantial fraction of their mass during their post-main-sequence evolution and they suggest the remnants of such stars would be white dwarfs rather than neutron stars (and black holes). Even if such processes are operative, however, the presence of some massive stars is clearly indicated. There are a number of H II regions within  $15'$  of Sgr A\* which appear to be powered by OB and/or WR stars (e.g., Figer, McLean, & Morris 1996; Poglitsch et al. 1996); observations of H<sub>2</sub> ( $v = 1 \rightarrow 0$ ) S(1) emission in the inner  $2^\circ$  imply excitation by a UV radiation field (Pak, Jaffe, & Keller 1996); and star counts within the inner  $2^\circ$  reveal a number of stars with dered-

dened absolute magnitudes of  $M_K \lesssim -9$ , suggestive of stars with  $M \gtrsim 5 M_\odot$  (Catchpole, Whitelock, & Glass 1990; Bertelli et al. 1994). Bearing these caveats in mind, we shall use our estimate of  $10^7$ – $10^8$  neutron stars in the GC.

The actual number of active *and detectable* pulsars in the GC will be substantially smaller. Firstly, the mean space velocity of pulsars is  $500 \text{ km s}^{-1}$  (Lyne & Lorimer 1994). A considerable fraction,  $\gtrsim 0.25$ , is not bound to the Galaxy. Only those pulsars forming the lowest-velocity tail,  $\lesssim 100 \text{ km s}^{-1}$  or about 16% of the objects, are bound to the central 100 pc. Secondly, the lifetime for pulsar radio emission is  $\sim 10^7 \text{ yr}$  for strong field objects with surface fields  $\sim 10^{12} \text{ Gauss}$ . If the Galactic bulge is  $\sim 10^{10} \text{ yr}$  old, only a fraction  $\sim 10^{-3}$  of the neutron stars formed in the central 100 pc will still be active pulsars. Hence, of the  $\sim 10^7$ – $10^8$  neutron stars formed in the GC over the lifetime of the Galaxy,  $\sim 10^3$ – $10^4$  are likely to be active pulsars still within the central 100 pc. Of these, only a fraction  $f_b \sim 0.2$  will be beamed toward us (Biggs 1990; Lyne & Manchester 1988; Narayan & Vivekanand 1983). If about 1% of these can be detected, as in an imaging survey using the VLA, then only a few to  $\sim 20$  objects are expected to be found. A periodicity search that finds only the 0.1% most luminous pulsars is unlikely to find any pulsars from this population.

One effect which would increase this number is the production of recycled pulsars in binaries resulting from tidal captures and stellar collisions. The central stellar density may exceed  $10^7 \text{ pc}^{-3}$ , sufficiently high that stellar encounters should be frequent and that processes for recycling pulsars should be operative. Fabian, Pringle, & Rees (1975) estimate the tidal capture rate (see also Hut et al. 1992). If the number of neutron stars formed in the GC has been  $\sim 10^7$ – $10^8$ , then  $\sim 10^3$  tidal captures or collisions will have occurred over the Galaxy’s history. Not all of the binaries so formed will produce a recycled pulsar and primordial binary systems could also contribute to the population of recycled pulsars. Regardless of formation mechanism, the detection of a large number of soft, compact X-ray sources toward the GC (e.g., Predehl & Trümper 1994) supports the possibility of an enhanced number, relative to the disk, of neutron-star binary systems in the GC. Although some of these X-ray sources are probably black-hole systems, the fraction of millisecond pulsars in the total pulsar population in the GC could nevertheless be enhanced substantially relative to a value  $\sim 0.5$  in the

disk (Bailes & Lorimer 1995; Lorimer et al. 1993).

Unfortunately, the fastest spun-up pulsars will not be detectable in a periodicity search, though they may appear in an imaging search. Modestly spun-up pulsars with lifetimes 10–100 times longer than those of most pulsars may be the best targets. In this respect it is interesting that 15% of the spun-up pulsars in a recent listing had periods greater than 100 ms (Kulkarni 1995), though none of these objects would themselves be detectable if placed at the GC.

## 6.2. Star Bursts

The discussion above assumes a constant star formation rate within the GC. A recent starburst has been invoked (e.g., Hartmann 1995; Genzel et al. 1994; Sofue 1994; but see also Morris 1993) to explain one or more features of the GC. Estimates for the age of the burst are  $10^6$ – $10^7 \text{ Myr}$  with the total number of neutron stars formed being  $10^2$ – $10^6$ . Even if a burst per se has not occurred, several lines of evidence point to an enhanced star formation rate, relative to the disk rate, during the recent past in the GC. These include the density of supernova remnants within the central  $10^\circ$  which is double that found in the disk (Gray 1994), and the presence of a large number of shell and arc structures in molecular gas, also suggestive of recent supernova activity (Hasegawa et al. 1996).

The estimated range of ages for the most recent starburst is sufficiently small that all of the pulsars formed during the burst should still be active. High velocity pulsars will escape the GC in a time short compared to the burst. Indeed, Hartmann (1995) advocates searches for these escaped pulsars as a means for diagnosing the recent star formation history in the GC. Depending upon the number of neutron stars created in the burst, the total number of pulsars in the GC from the low-velocity tail of the pulsar velocity distribution could number  $10$ – $10^5$ . That is, the number of active pulsars from the burst population could exceed that from a constant star formation rate over the history of the GC.

The number of detectable pulsars will be smaller than the total number active and within the GC due to selection effects. In §§4 and 5 we estimated the fraction of pulsars sufficiently luminous to be detected,  $f_L$ , based on the local pulsar luminosity function. This fraction is  $10^{-2}$ – $10^{-5}$ , depending upon the search method and frequency. Taking into account

the non-isotropic nature of pulsar emission, the resulting fraction of detectable pulsars is  $\sim 10^{-3}$ – $10^{-6}$ . Thus, the number of active, detectable pulsars from the central 100 pc of the Galaxy could be  $\lesssim 1$  to as many as 100. A constant star formation rate over the GC’s history will likely contribute  $\lesssim 10$  pulsars to the total number detectable.

### 6.3. Pulsars as Probes of the Galactic Center

We conclude this section with a brief discussion of the utility of pulsars for constraining the dynamics and star formation history of the GC. The number of pulsars detected, together with a careful accounting for selection effects, can be used to constrain the past star formation rate of the GC. If any pulsars can be detected as sources of pulsed emission, the distribution of spin periods; their period derivatives,  $\dot{P}$ ; and dispersion measures, DM, and pulse broadening should also be measurable. The distribution of periods can be used in estimating the past star formation rate (e.g., Lorimer et al. 1993). Measurement of  $\dot{P}$  has the potential to constrain the GC gravitational potential, much like the determination of a negative  $\dot{P}$  for B2127+11 has set limits on its acceleration from the potential of the globular cluster M15 (Wolszczan et al. 1989). As noted in §1, the most recent model for the Galactic distribution of ionized gas has few constraints toward the inner Galaxy. Even a few DM and pulse broadening measurements would prove useful for improving substantially our knowledge of conditions there. Moreover, gas velocities, particularly near Sgr A\*, are large, in some cases exceeding  $100 \text{ km s}^{-1}$  (Schwarz, Bregman, & van Gorkom 1989). DM monitoring programs can expect to detect changes in the DM on time scales of a month, which in turn could be used to probe the AU-scale structure of ionized gas in the GC. Even if pulsars can only be detected in an imaging survey, their angular diameters would still provide both constraints on the distribution and a probe of the small-scale structure of ionized gas in the GC.

Finally, the clock-like nature of pulsars has prompted speculation about their utility for studying the constituents and mass distribution in the GC. Wex, Gil, & Sendyk (1996) and, earlier, Paczynski & Trimble (1979) have discussed the microlensing and gravitational time delay of GC pulsars. The time delay, in particular, can be used to constrain the mass of any central object. Such determinations, however, will be possible at only the highest frequencies where pulsed

emission is manifested.

## 7. CONCLUSIONS AND RECOMMENDATIONS

The extreme level of scattering seen toward the Galactic center ( $1.3''$  of broadening for Sgr A\* at 1 GHz) produces considerable pulse broadening. The amount of pulse broadening depends upon the Galactic center-scattering screen distance,  $\Delta_{\text{GC}}$ , but at minimum, the pulse broadening is 6.3 *seconds*. If the screen is closer to the Galactic center, the pulse broadening is increased. Radio pulsars within about  $15' - 1^\circ$  of Sgr A\* and behind the GC scattering screen will only be detected by periodicity searches conducted at frequencies much higher than used heretofore *or* by imaging surveys.

Periodicity searches at 5 GHz will be capable of detecting pulsars with canonical spin periods  $\sim 1 \text{ s}$ , though with much reduced sensitivity if  $\Delta_{\text{GC}} \ll D_{\text{GC}}$ . At 10 GHz, pulse broadening of millisecond pulsars is a significant fraction of a period even if  $\Delta_{\text{GC}} \approx D_{\text{GC}}$ . If  $\Delta_{\text{GC}} \sim 100 \text{ pc}$ , pulsars with periods shorter than 0.5 s at 5 GHz and 34 ms at 10 GHz will be inaccessible. To reach pulsars with the Crab pulsar’s period (33 ms) such that a 10% duty cycle pulse may be seen without broadening, the observing frequency must be at least 18 GHz. While the Crab pulsar itself is undetectable at this frequency, other young pulsars with shallower spectra (e.g., Lorimer et al. 1995) may be strong enough. Such objects are rare, so we conclude that imaging surveys at fairly low frequencies (e.g., 1.4 GHz) are much more likely to be successful in finding Galactic center pulsars.

The optimal frequency for conducting any periodicity searches is that which maximizes the pulsed flux density and is given by  $\nu_{\text{max}} = 7.3 \text{ GHz} (\sqrt{\alpha} \Delta_{0.1} P)^{1/4}$  (Eq. 11). The effective duty cycle of a scattered pulsar at the optimal frequency is  $\approx 0.2\sqrt{\alpha}$  and suggests that search algorithms need not consider more than  $\epsilon_{\text{eff}}^{-1} \sim 5$  harmonics in the DFT.

The angular broadening for a pulsar at the GC will be similar to that of Sgr A\*; the broadening for a pulsar more distant than Sgr A\* but seen through the same scattering screen is given by Eq. 14. These angular sizes are well matched to the synthesized beams of the VLA in its four configurations.

Finally, the number of pulsars detectable in the Galactic center depends upon the star formation history of the Galactic center. The largest number of

detectable pulsars will occur if the GC has undergone a recent episode ( $\lesssim 10^7$  yr) of massive star formation. The number of active, detectable pulsars in the GC may be as many as 100. Smaller starbursts and the star formation over the Galaxy's history can contribute another 1–10 pulsars.

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